Proceedings of Indian River Lagoon Symposium 2020

Risks to Indian River Lagoon biodiversity caused by climate change.

Randall W. Parkinson(1,2), Valerie Seidel(3), Clay Henderson(4), and Duane De Freese(5)

(1)Institute of Environment, Sea Level Solutions Center, Florida International University, 11200 SW 8th Street, OE-148, Miami 33199
(2)RWParkinson Consulting, Inc., 322 Coral Drive, Melbourne, FL 32935
(3)The Balmoral Group, 165 Lincoln Avenue, Winter Park, FL 32789
(4)Stetson University, 421 N Woodland Blvd, DeLand, FL 32723
(5)Indian River Lagoon National Estuary Program, 1235 Main Street, Sebastian, FL 32958

Abstract Estuaries are especially sensitive to climate change because they are located at the land-sea interface and therefore water quality, habitat value, and ecosystem function are largely determined by what is being input to the basin from the adjacent terrestrial and marine environments. As climate changes, estuarine resilience is likely to be compromised as upland rainfall and river flow patterns change, air and water temperatures rise, intensity and frequency of tropical storm and hurricane landfalls increase, pH declines, and sea-level rises. Here, we demonstrate that future risks to the biodiversity of the Indian River Lagoon, Florida, caused by climate change can be effectively mitigated by implementing nine adaptation actions. Each was designed to reduce septic, wastewater, and surface water pollutant loadings that are expected to increase in response to one or more of the three principle climate change stressors identified during this evaluation: changes in precipitation, increasing storminess, and sea-level rise. By reducing pollutant loadings from these three sources, impairments to water quality and their deleterious effects on biodiversity will be ameliorated. Implementation and management of these plans will require a substantial increase in funding that is coherently managed for decades. Strengthened collaboration between local, state, and federal programs will be necessary to enhance the probability of success.

Keywords Adaptation Action Plan, Biodiversity, Climate Change, Vulnerability Assessment, Water Quality Impairment

Introduction

The Earth's climate is changing. Temperatures are rising. Snow, rainfall, and river flow patterns are shifting, and more extreme climate events—like heavy rainstorms and record-high temperatures—are already taking place more frequently (National Academies of Sciences, Engineering, and Medicine 2016). Estuaries are especially sensitive to these changes because they are located at the land-sea interface and therefore water quality, habitat value, and ecosystem function are largely determined by what is being input to the basin from the adjacent terrestrial and marine environments. As climate changes, so will these two adjacent environments, causing an estuary's resiliency to be compromised as upland rainfall and river flow

---

Corresponding author: Randall Parkinson, rparkins@fiu.edu patterns change, air and water temperatures rise, intensity and frequency of tropical storm and hurricane landfalls increase, sea-level rises, and pH declines (Gillanders et al. 2011, Statham 2012, James et al. 2013, Robins et al. 2016, Gregg et al. 2017). The resilience of an estuary under conditions of a changing climate is further stressed if the system is currently impaired by the effects of coastal urbanization and concomitant water quality degradation due to elevated pollutant loadings (e.g., sediment, nitrogen, phosphorous).

In recognition of these challenges, the United States Environmental Protection Agency (EPA) established the Climate Ready Estuaries Program (CRE) in 2008 to provide assistance to the National Estuary Programs (NEPs) (Gregg 2010). The CRE was established as a partnership between the EPA and the NEPs to address the impact of climate change on Estuaries of National Significance (ENS). The CRE mission is to support NEPs and their coastal communities in becoming "climate ready" by providing tools and assistance to (1) conduct a risk-based assessment of an estuary's vulnerability to climate change and (2) develop and implement adaptation actions to reduce those risks. However, by 2011 only one of the NEPs had undertaken efforts to become climate ready (Charlotte Harbor National Estuary Program 2010). Based on the EPA's experience with watershed management, a workbook was developed to assist the remaining NEPs in becoming climate ready (EPA 2014). By the time the project described herein was initiated in 2017, eight of the 28 NEPs had undertaken a risk-based vulnerability assessment following workbook guidelines and one had completed an adaptation action plan (Bauza-Ortega 2015).

The Indian River Lagoon (IRL) contains 27% of Florida's eastern coastal wetlands and is possibly home to more species than any other estuary in North America, including some 4,300 plant and animal species (St. Johns River Water Management District 2007). To facilitate the protection and restoration of water quality and ecological integrity, the IRL was recognized by the EPA as an ENS in 1990. Thereafter, research designed to enhance the knowledgebase from which to formulate and implement a Comprehensive Conservation and Management Plan (CCMP) quickly expanded. What followed was growing evidence that the ecological and biological integrity of the lagoon had degraded over the past 50 years due to a decline in water quality caused by (1) pollution from point and nonpoint sources, (2) disruption in the natural patterns of water circulation in the lagoon, and (3) alterations in freshwater inflows, especially during wet season discharges (Sigua et al. 2000). In this paper, we describe the (1) results of a risk-based vulnerability analysis of IRL biodiversity (e.g., species richness and abundance) caused by climate change and (2) nine mitigative adaptation actions designed to stimulate the emergence of a more resilient, climate ready estuary.

Materials and Methods

Study location. The Indian River Lagoon (Figure 1) covers an area of 353 km^2 and is composed of three distinct and connected estuaries: the Indian River, Banana River, and Mosquito Lagoon. The Lagoon stretches along 156 miles of coastline and encompasses almost 40% of Florida's east coast. Its

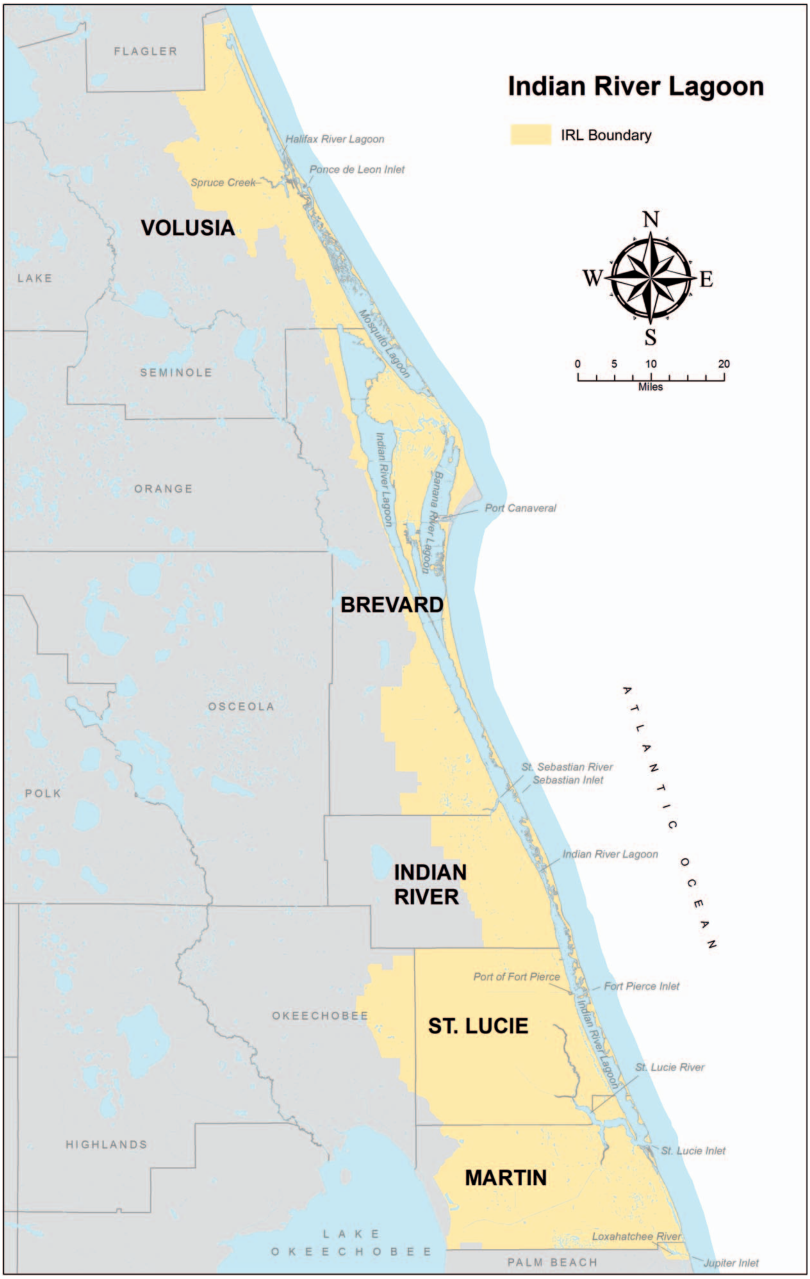

Figure 1. Location map of Indian River watershed that includes five coastal counties and two upland counties (Okeechobee, Palm Beach), the latter two of which were integrated into the natural watershed upon construction of surface water conveyance and storage infrastructure in the early 20th century.

2,284 km^2 watershed sprawls over five counties and spans two climate zones: temperate and subtropical. Two additional counties (Okeechobee, Palm Beach) were integrated into the watershed upon the construction of surface water storage and conveyance infrastructure in the early part of the 20th century. Thirty-eight incorporated cities and approximately 1.6 million residents live within the boundaries of the watershed. Its total economic contribution to the region is estimated to be about ten billion dollars, generated by five IRL-related industry groups; living resources, marine industries, recreation and visitor, resource management, defense and aerospace, marine industries, and tourism (East Central Florida Regional Planning Council and Treasure Coast Regional Planning Council 2016).

Part 1. Vulnerability assessment. As an initial task, we conducted a vulnerability assessment to identify and prioritize risks to biodiversity caused by climate change. First, it was necessary to identify what climate change stressors should be considered. To accomplish this task, the project team (1) reviewed all existing risk-based vulnerability assessments conducted for NEPs located within the state of Florida (i.e., Charlotte Harbor National Estuary Program 2010; Shafer et al. 2017; Tampa Bay Estuary Program 2017), as well as California and Puerto Rico (Bauza-Ortega 2015; Grubbs et al. 2016), (2) solicited stakeholder and practitioner input, and (3) conducted a literature review of relevant, climate-related investigations (NOAA, 2010, Beever III et al. 2012, Ingram et al. 2012, Pachauri et al. 2014, Chassignet et al. 2017, Sweet et al., 2017, USGCRP, 2018, The National Academy of Sciences and The Royal Society, 2020).

The second task was to identify specific risks to IRL biodiversity goals, as defined in the CCMP (Indian River Lagoon National Estuary Program 2019), caused by the principle climate change stressors. A core component of the IRLNEP CCMP is the vital signs wheel (Figure 2). It includes three missions (e.g., One Lagoon), five categories (formerly goals, e.g., Water Quality, Living Resources), and 32 vital signs (e.g., Impaired Waters, Biodiversity). The vital signs were created as critical indices to measure progress in each category and corresponding mission. Associated with each vital sign is one or more action plans formulated to promote specific activities to facilitate category progress. Action plans that contained biodiversity goals and related outputs that could be compromised by climate change were subject to a risk analysis with regards to the following parameters: consequence, likelihood, spatial scale, and timeline (Table 1). We assigned a value between 1 (minimal threat) and 3 (maximum threat) based upon the knowledge and experience of the project team and scored each based upon the sum of those values as described in the EPA Workbook. Next, the risks were prioritized by assigning each to one of three risk categories based upon the risk analysis score: highest, higher, and high. This effort benefited enormously from the constructive comments and recommendations of more than 40 stakeholders and practitioners, as well as those in attendance of professional meetings and workshops (e.g., Northeastern Estuarine Research Team, East Central Estuarine Research Team), during which the project results were presented at various stages of completion.

Part 2. Adaption actions. Part 2 of the investigation entailed the formulation of new adaptation actions that could be undertaken to reduce climate-related risks to the IRL biodiversity mission identified in Part 1. An adaptation action was, for the purposes of this investigation, a specific activity designed to reduce one or more highest-priority risks to IRL vital signs caused by climate change. The adaptation actions were developed by the authors based upon the combined experience of the team from a resource optimization perspective intent on formulating the fewest number of adaption actions that could reduce the largest number of the highest-level biodiversity risks.

Results

Part 1 – Vulnerability assessment. Climate change stressors—Analysis of the suite of climate change stressors identified by other NEPs that had already completed a vulnerability assessment yielded five that we considered relevant to the IRL. Examples of how each puts biodiversity at risk are shown in Table 2. The rationale and consequence of each are described in the following sections.

Figure 2. Vital signs wheel created by IRLNEP to communicate the program's mission. The five categories and 32 vital signs located in the outer two layers were the focus of this investigation.

Table 1. Parameters and corresponding numeric values used in risk analysis to score and rank risks to bio diversity caused by climate change. Modified from EPA (2014).

Consequence	Spatial extent of impact
1. Low (could adjust, life will go on)	1. Site (bridge, stormwater outflow)
2. Medium	2. Area (community, wildlife refuge)
3. High (catastrophic, major disruption)	3. Region (watershed)
Likelihood	Time horizon
1. Low (unlikely)	1. >10 years
2. Medium	2. 5 – 10 years
3. High (very likely, predictable)	3. Already occurring or <5 years

Table 2. Example of risks to IRL biodiversity caused by climate change. SWSC = surface water storage and conveyance infrastructure, WWTP = wastewater treatment plant, OSTDS = onsite sewage treatment and disposal system.

Climate Stressor				
Warmer temperatures	Changes in precipitation	Increasing storminess	Acidification	Sea level rise
Elevated pollutant loading caused by temperature-induced changes in solubility and/or toxicity	Polyhaline conditions caused by intervals of higher rainfall and extended periods of drought	Increased pollutant loading from overtaxed SWSC	Decreased vitality of calcifying organisms (e.g., shellfish) and other habitat-dependent taxa	Increased pollutant loading from WWTPs and OSTDSs caused by rising water table and sea level (inundation, erosion)

Warmer temperatures—Warmer temperatures are one of the most obvious signs of climate change. Concentrations of heat-trapping greenhouse gases are increasing in the Earth's atmosphere. In response, average temperatures at the Earth's surface are increasing and expected to continue rising. In the IRL watershed, the average annual temperature has risen by 1 °C since 1895 (Parkinson and Seidel 2018). Robbins and Lisle (2017) found no significant change in monthly averages of IRL water temperature collected over the past 15 years. However, rising atmospheric temperatures are expected and will ultimately result in an increase in IRL water temperatures. Rising water temperatures will trigger changes in water quality and clarity (e.g., salinity, DO, Chl-a) (Doney 2010, Cai et al. 2011, Sherwood 2016).

Changes in precipitation—As the average temperature at the Earth's surface rises, more evaporation occurs. This in turn can locally increase or decrease rainfall (e.g., timing, rate, duration). In Florida, a decline in average precipitation has been observed over the last decade (Runkle et al. 2017). Historically, the number of high-intensity rain events (greater than 4 inches/day) in Florida has been highly variable; however, the highest number of days with more than 4 inches of rain occurred during the current decade (2010–2014) (Runkle et al. 2017). In the IRL watershed, analyses of historical data indicate a tendency towards drier spring and fall conditions and wetter winters (Easterling et al. 2017). In a study by Dourte et al. (2015), rain-gauge stations in the IRL watershed showed a substantial increase in extreme rains (>6 in/day) over the last 30 years when compared to the previous 30-year period. These observations suggest high-intensity rain events are becoming more common and will continue to rise under conditions of a changing climate. The combination of extended intervals of drier conditions punctuated by more frequent cloud bursts will likely lead to changing temporal and spatial salinity patterns and a significant reduction in water quality, as pollutants amassed during weeks to months of drier weather are discharged into the IRL watershed over a short period of time (hours to days).

Increasing storminess—This category considers the forecasted increase in the frequency and intensity of hurricanes, tropical storms, and other intense rotating storms. Recent modeling suggests storms will become more intense over the 21st century (Knutson et al.,2010, Dow et al. 2013, EPA, 2016). The combined and most relevant effects of increased storminess on the IRL will be an increase in the flux of freshwater (stormwater runoff), erosion (waves and currents), flooding (storm surge), and destruction (rainfall, wind, waves, currents, storm surge) during event conditions.

Acidification—Atmospheric carbon dioxide is predicted to increase throughout this century and so too is ocean acidity, as more greenhouse gas is absorbed at the air-sea interface. Over the past 13 years, Robbins and Lisle (2017) reported an increase in IRL acidification. The increase in acidity can harm or kill juvenile fish (Baumann et al. 2012, Frommel et al. 2012) and makes it more difficult for calcifying taxa to produce and maintain their shells or skeletons (Hoegh-Guldberg et al. 2007, Miller et al. 2009).

Table 3. Summary of climate change stressors and risks to IRL. PPt = changes in precipitation. Storms = increased storminess. SLR = sea-level rise. Accept = risk accepted as eminent or insignificant.

	Stressor						Level of Risk				
Category and Vital Sign	Temp	PPt	Storms	pH	SLR	Sum	Accept	Highest	Higher	High	Sum
Water Quality											
Impaired waters	5	54	57	0	55	171	5	162	4	0	166
Wastewater	1	10	10	1	10	32	2	30		0	30
Stormwater and surface water	5	8	8	1	9	31	3	24	2	2	28
Hydrology and hydrodynamics	3	3	0	0	3	9	0	3	6	0	9
Legacy loads and healthy sediments	0	0	1	0	0	1	0	0	1	0	1
Atmospheric deposition	1	1	1	0	0	3	3	0	0	0	0
Sum	15	76	77	2	77	247	13	219	13	2	234
Habitats											
Seagrass	6	16	15	1	14	52	5	47	0	0	47
Living shorelines	1	1	2	1	2	7	3	0	4	0	4
Wetlands and impounded/ altered marshes	3	1	0	0	2	6	5	1	0	0	1
Sum	10	18	17	2	18	65	13	48	4	0	52
Living Resources											
Biodiversity	3	16	11	1	17	48	5	33	10	0	43
Species of concern	10	15	18	1	19	63	4	47	12	0	59
Invasive species	2	15	14	0	14	45	3	14	28	0	42
Commercial and recreational fisheries	3	15	19	1	14	52	4	42	6	0	48
Sum	15	45	51	2	47	160	11	103	46	0	149
Grand Total	40	139	145	6	142	472	37	370	63	2	435

Sea level rise—As the temperature of the Earth changes, so too does the elevation of global eustatic sea level. This is because rising temperatures cause an increase in the flux of glacial and ice sheet meltwater into the ocean, causing sea level to rise. Second, seawater expands as it warms, causing an increase in the height of sea level. The most recent global eustatic sea-level rise scenarios (USACE 2013, Sweet et al. 2017) suggest it will reach elevations of between 0.2 and 0.6 m above present by 2050 and 0.3 to 2.5 m by the end of this century. This will lead to the inundation of low-lying coastal areas, shoreline erosion, and saltwater intrusion. Higher sea level elevations are also expected to increase the frequency, extent, and duration of flooding during storm events.

Risk analysis and prioritization—Results of our biodiversity risk analysis indicated 31 of 102 IRLNEP action plans could be compromised by one or more of the five climate change stressors. Because each of the five climate change stressors could result in more than one risk to an action plan or impact multiple action plans, the number of stress-related risks to biodiversity were much larger than the number of action plans being stressed (Table 3). For example, warmer temperature was determined to put the Impaired Waters vital sign at risk to: (1) increasing Chl-a concentrations due to more frequent algal blooms, (2) decreasing DO solubility and (3) availability due to more frequent algal blooms and (4) and acceleration in the

Table 4. Adaptation Actions proposed to reduce risks to the IRL biodiversity caused by climate change. WWTP = wastewater treatment plant, OSTDS = on site treatment and disposal system, SWSC = surface water storage and conveyance infrastructure.

Stressor	Adaptation Action
Changes in precipitation	1. Reduce pollutant loadings from WWTP during high rainfall events
	2. Reduce pollutant loadings from OSTDS during high rainfall events
	3. Reduce pollutant loadings from SWSC infrastructure during high rainfall events
Increasing storminess	4. Reduce pollutant loadings from WWTP due to more frequent and intense storms
	5. Reduce pollutant loadings from OSTDS due to more frequent and intense storms
	6. Reduce pollutant loadings from SWSC infrastructure due to more frequent and intense storms
Sea-level rise	7. Reduce pollutant loadings from WWTP caused by rising water table and sea level (inundation, erosion)
	8. Reduce pollutant loadings from OSTDS caused by rising water table and sea level (inundation, erosion)
	9. Reduce pollutant loadings from SWSC infrastructure caused by rising water table and sea level (inundation, erosion)

decomposition of organic matter, and finally (5) decreasing water clarity due to increased growth rates and survival of algae and related taxa. A total of 472 risks were identified, of which 48 (10%) were to Biodiversity vital signs. Fifty percent of all risks were associated with three vital signs: Impaired Waters, Wastewater, and Surface Water. But many of these risks will also compromise biodiversity. For example, increased pollutant loading from on-site treatment and disposal system (e.g., septic) failures caused by a rising water table and sea level will trigger more frequent algal blooms, reduce DO availability and negatively impact biodiversity. Ninety-seven percent of all risks were induced by three climate change stressors: change in precipitation, increasing storminess, and sea-level rise. Ninety-one percent of the risks to biodiversity were driven by these same three stressors.

Part 2. Adaption actions. An adaptation action was, for the purposes of this investigation, a specific activity designed to reduce one or more highest-priority risks to IRL vital signs caused by climate change. Based upon the results of Part 1, we formulated nine adaption actions to reduce water quality impairment by targeting the primary sources of elevated pollutant loadings anticipated to accompany the predominant climate change stressors: wastewater treatment plants (WWTP), onsite treatment and disposal systems (OSTDS), and surface water storage and conveyance infrastructure (SWSC) (Table 4). If successful, these actions will also modulate threats to many other vital signs not specifically targeted by these actions.

Discussion

We propose nine adaptation actions to reduce the potential loss of IRL biodiversity caused by three climate change stressors: changes in precipitation, increasing storminess, and sea-level rise. Each is designed to address increased pollutant loadings and concomitant water quality impairment derived from WWTP, OSTDS, SWSC. Based upon our analysis, the successful implementation of these plans will significantly enhance the prognosis of IRL biodiversity to climate change.

The next challenge to the IRLNEP will be to implement and monitor specific action plans designed to achieve the goal of each adaptation action. This will require a commitment of billions of dollars to identify and fund projects that will have to be implemented and sustained over generations (Sherwood 2016, Lefcheck et al. 2018, Beck et al. 2019). Since inception, the IRLNEP has consistently supported projects designed to improve water quality, habitat value, and ecosystem function. However, financial support for this type of work is limited (~\$500,000 per year) because the program was not created as a stand-alone means with which to restore the lagoon. Over the past few years, new funding has become available through local, state, and federal initiatives (e.g., Save our Indian River Lagoon, Brevard County; various Florida House of Representative bills; The Protect and Restore America's Estuaries Act, US House of Representatives). Funding through these initiatives now exceeds \$0.5 billion, but more will be required.

Equally important will be the ability to track implementation, progress, and success of the action plans within a 2,284 km^2 watershed that spans the jurisdictional boundaries of five counties, two water management districts, and several state regulatory agencies (e.g., Florida Department of Environmental Protection, Florida Agricultural and Consumer Services). To meet these challenges, the existing partnership between the state of Florida and the IRLNEP will have to be expanded and codified. The efficacy of this partnership is favorable given both programs have a dedicated leadership structure, common goals, an established stakeholder network, funding stream, and monitoring / reporting protocol. By working together over the decades ahead and following the guidelines of adaptive management, is seems possible to improve the IRL's water quality, reduce impairment, and stimulate the emergence of a more resilient and biodiverse climate ready estuary.

Acknowledgments This work was supported by the Indian River Lagoon Council under Grants IRL2017-01 (Risk-based Vulnerability Assessment) and IRL2017-12 (Adaptation Planning). Thanks to Charles (Chuck) Jacoby (St. John's River Water Management District), Kathy Hill (Indian River National Estuary Program), and all the practitioners and stakeholders who provided constructive input throughout the duration of this three-year project. This is publication number 34 of the Institute of Environment, Sea Level Solutions Center, Florida International University, Miami, FL 33199.

Declaration of interest statement This is to acknowledge there exists no financial interest or benefit arising from the direct applications of this research.

References

Baumann H, Talmage SC, Gobler CJ. 2012. Reduced early life growth and survival in a fish in direct response to increased carbon dioxide. Nature Climate Change 2:38–41.

Bauza-Ortega J. 2015. San Juan Bay Estuary climate change adaptation plan. San Juan Bay Estuary Program, San Juan, PR.

Beck MW, Sherwood ET, Henkel J.R, Dorans K, Ireland K, Varela P. 2019. Assessment of the cumulative effects of restoration activities on water quality in Tampa Bay, Florida. Estuaries and Coasts. 42:1774–1791.

Beever III J, Council, SFRP, Gray W, Cobb D, Walker T. 2012. Climate change vulnerability assessment and adaptation opportunities for salt marsh types in Southwest Florida. Southwest Florida Regional Planning Council. Fort Myers FL.

Cai W-J, Hu X, Huang W-J, Murrell M, Lehrter J, Lohrenz S, Chou W-C, Zhai W, Hollibaugh J, Wang Y, Zhao P, Guo, X, Gundersen K, Dai M, Gong G-C. 2011. Acidification of subsurface coastal waters enhanced by eutrophication. Nature Geoscience 4:766–770.

Charlotte Harbor National Estuary Program, 2010. Charlotte Harbor regional climate change vulnerability assessment. Charlotte Harbor National Estuary Program. Punta Gorda FL.

Chassignet E, Jones J, Misra V, Obeysekera J. 2017. Executive summary *in* Florida's Climate: Changes, Variations, & Impacts. Florida Climate Institute. http://purl.flvc.org/fsu/fd/FSU_libsubv1_scholarship_submission_1516136446_ca81fc00

Doney SC. 2010. The Growing human footprint on coastal and open-ocean biogeochemistry. Science 328:1512–1516.

Dourte, D.R., Fraisse, C.W., Bartels, W.-L., 2015. Exploring changes in rainfall intensity and seasonal variability in the Southeastern U.S.: Stakeholder engagement, observations, and adaptation. Climate Risk Management 7:11–19.

Dow K, Anderson, J, Brosius A, Diaz E, Durbrow R, Evans R, Fauver S, Hayden T, Howard B, Jacobs K, Landers G, McNulty S, Nicholson J, Quattrochi D, Rimer L, Shuford S, Stiles S, Terando A. 2013. Chapter 13. Climate adaptations in the Southeast USA. US Environmental Protection Agency Papers. 214.

East Central Florida Regional Planning Council, Treasure Coast Regional Planning Council, 2016. Indian River Lagoon Economic valuation update 2016. Florida Department of Economic Opportunity, Tallahassee FL.

Easterling, DR, Kunkel KF, Arnold JR, Knutson T, LeGrande AN, Leung LR, Vose RS, Waliser DE, Wehner MF. 2017. Precipitation change in the United States. Pp. 207–0230 *in* Wuebbles DJ, Fahey DW, Hibbard KA, Dokken DJ, Stewart BC, Maycock TK, eds. Climate Science Special Report: Fourth National Climate Assessment, Volume I. US Global Change Research Program, Washington DC.

EPA 2014. Being Prepared for Climate Change A Workbook for Developing Risk-Based Adaptation Plans. EPA Climate Ready Estuaries. Washington DC.

EPA 2016. Climate Change Indicators in the United States. 2016. https://www.epa.gov/climate-indicators

Frommel AY, Maneja R, Lowe D, Malzahn AM, Geffen AJ, Folkvord A, Piatkowski U, Reusch TBH, Clemmesen C. 2012. Severe tissue damage in Atlantic cod larvae under increasing ocean acidification. Nature Climate Change 2:42–46.

Gillanders BM, Elsdon TS, Halliday IA, Jenkins GP, Robins JB, Valesini FJ. 2011. Potential effects of climate change on Australian estuaries and fish utilising estuaries: a review. Marine and Freshwater Research 62:1115–1131.

Gregg RM. 2010. U.S. Environmental Protection Agency's Climate Ready Estuaries Program. https://www.cakex.org/case-studies/us-environmental-protection-agency%E2%80%99s-climate-ready-estuaries-program.

Gregg RM, Reynier AS, Hilberg L. 2017. The state of climate adaptation in water resources management: Southeastern United States and the U.S. Caribbean. EcoAdapt, Brainbridge Island, WA.

Grubbs MW, Johnston KK, Wang G, Ford T. 2016. Climate Change Vulnerability Assessment of the Santa Monica Bay Estuary Program Bay Restoration Plan. Santa Monica National Estuary Program, Los Angeles, CA.

Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, Gomez E, Harvell CD, Sale PF, Edwards AJ, Caldeira K, Knowlton N, Eakin CM, Iglesias-Prieto R, Muthiga N, Bradbury RH, Dubi A, Hatziolos ME. 2007. Coral reefs under rapid climate change and ocean acidification. Science 318:1737–1742.

Indian River Lagoon National Estuary Program. 2019. Looking ahead to 2030 - A 10-year Comprehensive Conservation and Management Plan for the Indian River Lagoon. Indian River Lagoon National Estuary Program, Sebastian FL.

Ingram KK, Dow K, Carter L, Anderson J, Sommer EK. 2013. Climate of the Southeast United States: variability, change, impacts, and vulnerability. Island Press, Washington DC.

James N, van Niekerk L, Whitfield A, Potts W, Götz A, Paterson A. 2013. Effects of climate change on South African estuaries and associated fish species. Climate Research 57:233–248.

Knutson T, McBride JL, Chan J, Emanuel K, Holland G, Landsea C, Held I, Kossin JP, Srivastava AK, Sugi M. 2010. Tropical cyclones and climate change. Nature Geoscience 3:157–163.

Lefcheck JS, Orth RJ, Dennison WC, Wilcox DJ, Murphy RR, Keisman J, Gurbisz C, Hannam M, Landry JB, Moore KA, Patrick CJ, Testa J, Weller DE, Batiuk RA. 2018. Long-term nutrient reductions lead to the unprecedented recovery of a temperate coastal region. Proceedings of the National Academy of Sciences 115:3658–3662.

Lotze HK, Lenihan HS, Bourque BJ, Bradbury RH, Cooke RG, Kay MC, Kidwell SM, Kirby MX, Peterson CH, Jackson JB. 2006. Depletion, degradation, and recovery potential of estuaries and coastal seas. Science 312:1806–1809.

Miller AW, Reynolds AC, Sobrino C, Riedel GF. 2009. Shellfish face uncertain future in high CO_2 world: influence of acidification on oyster larvae calcification and growth in estuaries. PLoS One 4:e5661.

National Academies of Sciences, Engineering, and Medicine 2016. Attribution of Extreme Weather Events in the Context of Climate Change. National Academies Press, Washington DC.

NOAA 2010. Adapting to Climate Change: A Planning Guide for State Coastal Managers. Office of Ocean and Coastal Resource Management, Silver Springs MD.

Pachauri RK, Allen MR, Barros VR, Broome J, Cramer W, Christ R, Church JA, Clarke L, Dahe Q, Dasgupta P, and others. 2014. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. IPCC, Geneva Switzerland.

Parkinson RW, Seidel V. 2018. Climate change vulnerability assessment of the Indian River Lagoon National Estuary Program's Comprehensive Conservation and Management Plan. Indian River Lagoon National Estuary Program, Sebastian FL.

Robbins LL, Lisle JT. 2017. Regional acidification trends in Florida shellfish estuaries: a 20+ year look at pH, oxygen, temperature, and salinity. Estuaries and Coasts 41:1268–1281.

Robins PE, Skov MW, Lewis MJ, Giménez L, Davies AG, Malham SK, Neill SP, McDonald JE, Whitton TA, Jackson SE, Jago CF. 2016. Impact of climate change on UK estuaries: a review of past trends and potential projections. Estuarine, Coastal and Shelf Science 169:119–135.

Shafer D, Shafer J, Quigley C. 2017. Embracing our future - Sarasota Bay Estuary Program climate vulnerability assessment. Sarasota Bay Estuary Program, Sarasota FL.

Sherwood ET. 2016. Tampa Bay estuary: monitoring long-term recovery through regional partnerships. Regional Studies in Marine Science 4:1–11.

St. Johns River Water Management District 2007. Indian River Lagoon - an introduction to a national treasure. https://www.epa.gov/sites/production/files/2018-01/documents/58692_an_river_lagoon_an_introduction_to_a_natural_treasure_2007.pdf

Statham PJ. 2012. Nutrients in estuaries — An overview and the potential impacts of climate change. Science of The Total Environment 434:213–227.

Sweet W, Kopp R, Weaver C, Obeysekera J, Horton RM, Thieler ER, Zervas C.E. 2017. Global and regional sea level rise scenarios for the United States (Technical Report No. NOS CO-OPS 083). National Oceanic and Atmospheric Administration, Silver Springs, MD.

Tampa Bay Estuary Program 2017. Assessing the vulnerability of Tampa Bay Comprehensive Conservation and Management Plan Goal to the Effects of Climate Change (Technical Report No. 10B-17). Tampa Bay Estuary Program, Tampa Bay, FL.

The National Academy of Sciences, The Royal Society. 2020. Climate change: evidence and causes: update 2020. National Academies Press, Washington DC.

USACE 2013. Incorporating sea level change in civil works programs. United States Army Corps of Engineers. ER 1100-2-8162. Washington DC.

USGCRP 2018. Fourth National Climate Assessment. https://nca2018.globalchange.gov.

Submitted: July 13, 2020
Accepted: December 9, 2020